# Reproduction of Stained Glass on Transparent Substrate using Wide-Format Inkjet printer

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## Abstract

*A set of spectral transmittance data for 144 glass tiles (i.e. two test targets of 72 glass tiles each) was analyzed. Chromaticity coordinates and CIELAB values were calculated for each glass tile under two different illumination sources (A and D65). The colour differences ($\Delta E^*_{ab}$) for this pair of illuminants were examined, and the glass tiles with the largest errors were identified and their spectral transmittance curves plotted. A colorimetric reproduction of a stained glass panel was achieved. A digital camera was characterized using two stained glass test targets consisting of 72 glass tiles each. ICC profiles were created for a wide-format industrial inkjet printer for both single-pass and double-pass printing onto a transparent substrate (acetate). Reproductions of the stained glass panel were printed in both single-pass and double-pass modes, and evaluated for both colorimetric accuracy and subjective visual quality.*

## Introduction

Being a high dynamic range medium, stained glass has always been a challenge for imaging science, for example in the film photography of stained glass windows in historical buildings for conservation purposes. While their applications may have changed over the years, the basics of stained glass manufacturing have changed little. Oxides of transition metals are still used as the colorants in stained glass [1]. Today, stained glass is used for various purposes from airports to skyscrapers, making it a truly universal medium for interior design and architecture [2].

Previous research has investigated the capture of colour-accurate images of stained glass [3], [4]. One of the objectives of the European VITRA project [5] was direct acquisition by a digital camera of high-quality colorimetric images of stained glass windows in situ. Surprisingly, few attempts have been made to reproduce stained glass through print media. Even though in commercial practice ink-jet printing onto transparent material is routinely done, for example for backlit advertising displays, there has been no study as yet of the colour accuracy or systematic evaluation of results. The issues of measurement and reference viewing conditions for transparent (non-paper) substrates make them interesting for successful implementation of colour management systems.

## Stained Glass Colour Targets

Two stained glass test panels, the reference set and training set, were constructed and used as characterization test targets (Fig. 1). Each target contained 72 glass tiles of size 4×4 cm. These tiles were arranged in a rectangular layout of 8 rows by 9 columns, all within a bronze frame of dimensions 35×39 cm. In the reference test target the tiles were arranged with the darkest colours in the centre, in an attempt to minimize lens flare in photography. In the test target the tiles were randomized.

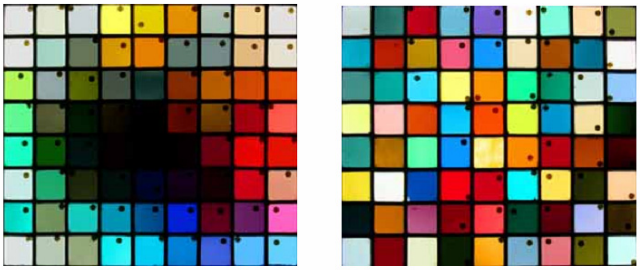

***Figure 1**. Reference test target (left) and training test target (right)*

Before being leaded into the panels, the glass tiles were measured individually using a Macbeth Color-Eye 7000A spectrophotometer to determine their transmission spectra. The spectral transmittance data were converted to colorimetric values using illuminants D65 and A. Fig. 2 shows the distribution of colours of the 144 glass tiles in the CIELAB $a^*$-$b^*$ and $L^*$-$C^*$ planes for both illuminants. These colours are well distributed over the colour space, ranging from near-neutral to highly saturated colours and from very light to very dark colours. The darkest tile (RB8) had a transmittance ($Y/Y_W$) of only 0.0137 under D65, corresponding to a lightness ($L^*$) of 0.124 and an optical density ($D_{max}$) of 3.86. In the $a^*$-$b^*$ plane it appears that the deviation between the points representing the colour of the glass tile under each illuminant is less near the centre (the origin). As the chroma increases (away from the centre) the deviation between the two points increases. Deviation between point pairs is highest in the lower-right quadrant ($+a^*$, $-b^*$). Thus, the glass tiles with red and blue components show the highest metamerism properties (or perhaps CIELAB is least uniform in this quadrant).

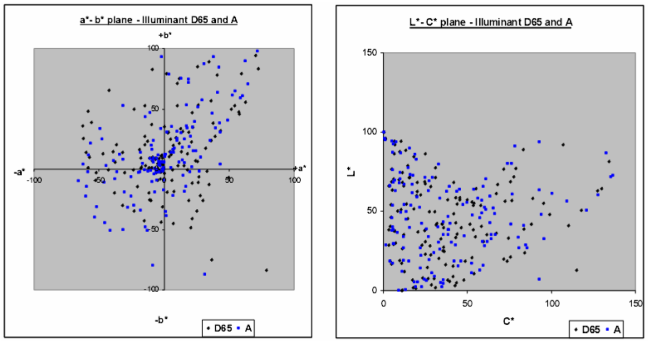

***Figure 2**. Distribution of stained glass tile colours in a*-b* (left) and L*-C* (right) planes for illuminants A and D65.*

In the $L^*$- $C^*$ plane in Fig. 2, it can be seen that the deviation between point pairs is less near the neutral ($L^*$) axis. Deviation between the corresponding points increases with the colourfulness. Thus, the metamerism of the glass tiles increases with colourfulness. Deviation is along the diagonal, meaning that the line through two corresponding points will pass through the origin (black point). For each glass tile the colour difference $\Delta E^*_{ab}$ was calculated between the corresponding colours for illuminants D65 and A. The resulting values of $\Delta E^*_{ab}$ were plotted against $L^*$, $C^*$ and $h$ for illuminant D65 (Fig. 3).

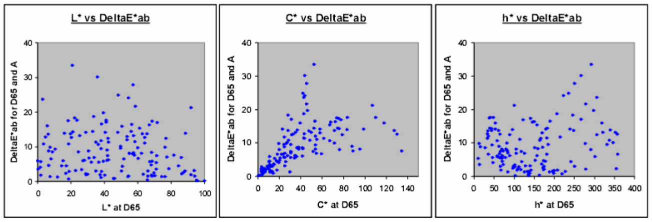

***Figure 3***. *Distribution of $E^*_{ab}$ values against L*, C* and h for illuminant D65.*

The $\Delta E^*_{ab}$ values are rather randomly distributed against lightness, but a clear trend can be seen against chroma, where there is a diagonal distribution. Thus $\Delta E^*_{ab}$ increases with chroma. Higher error values can be seen for hue angles in the range 220 to 330, i.e. for cyan, blue and purple tile colours. A histogram (Fig. 4) reveals an approximately exponential decline of the frequency of $\Delta E^*_{ab}$ colour difference values.

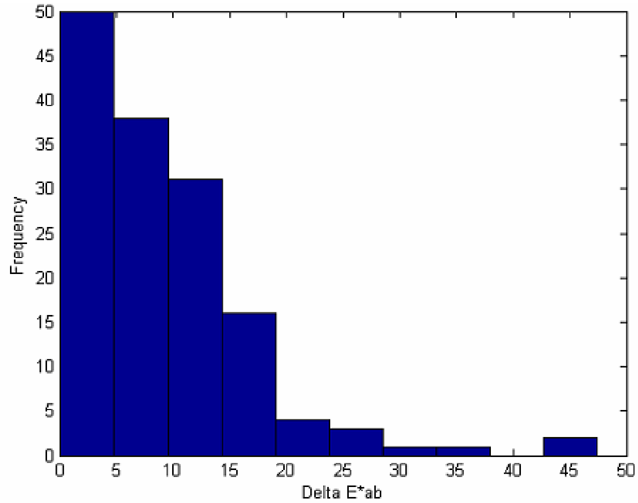

***Figure 4***. *Histogram of $\Delta E^*_{ab}$ difference values between illuminants D65 and A.*

The glass tiles with the largest $\Delta E^*_{ab}$ values (i.e. most metameric) can be found with the help of Fig. 3, and are the tiles designated RB4, RP7, TB5 and TB8. Fig. 5 shows their spectral transmittance curves, all of which have high transmittance in the short wavelength (violet and blue) region of the spectrum. They show almost zero transmittance for the long wavelength (orange and red) region. These problematical glass tiles can therefore be characterized by their high transmittance at short wavelengths and high negative slopes in the range 450 to 500 nm.

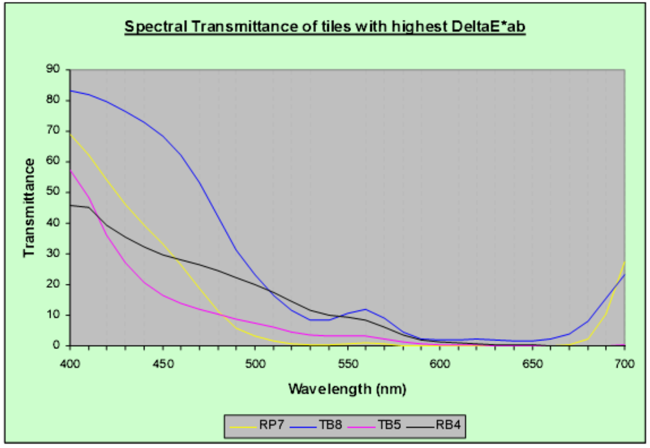

***Figure 5***. *Spectral transmittance curves of the four glass tiles with largest $\Delta E^*_{ab}$ values between illuminants D65 and A.*

## Characterization of Digital Camera

A large light table of size 106×118 cm, purpose-designed by Verivide for viewing of stained glass panels, was used to backlight the stained glass colour targets. The luminance level was maintained at 3350 cd/m$^2$. The glass panels were mounted on the light table and secured with the aid of sliding bars. The surface of the light table was covered by black cardboard outside the target area in order to minimize the flare light. The experimental setup for capturing the stained glass targets is shown in Fig. 6. A Leica Digilux II digital camera was used for photography, with lens aperture setting of *f* 8 and exposure speed of 1/60 second.

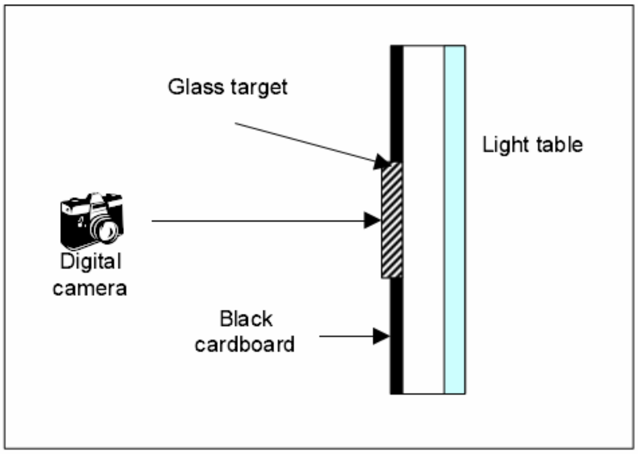

***Figure 6***. *Setup for image capture of stained glass targets.*

The non-uniformity of the illuminating surface was determined by capturing a 'white image' i.e. the light table without any glass target. Fig. 7 shows the illumination profile, as a function of luminance across the image area. The statistics of the distribution (pixel values) were:

$$\text{Max.} = 242 \text{ , Min.} = 228$$

$$\text{Mean} = 233\,, \ \text{Standard Deviation} = 1.71$$

Except at the extreme edge, the spatial uniformity of the white image was very good (Fig. 7), because of the careful design of the placement of the ten fluorescent tubes and diffuser within the light table. A correction for non-uniform illumination was applied to all images by dividing the average pixel values for the area within each glass tile by the corresponding relative luminance value of the white image. Thus, the output image was rectified as if illuminated by perfectly uniform lighting.

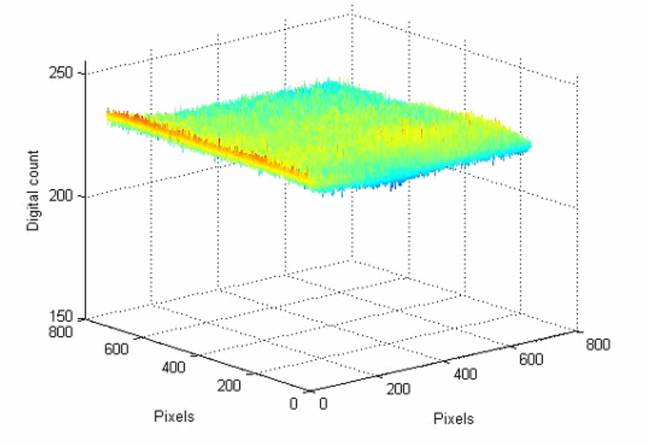

***Figure 7****. Spatial non-uniformity of white image.*

To characterize the camera, a polynomial regression method with least-square error minimization was applied. The accuracy of the characterization typically varies with the degree of polynomial. Higher-order polynomials give better performance, but above fourth-order they may significantly amplify unwanted noise. Previous studies show that a third-order polynomial generally gives sufficient accuracy [6], [7].

The coefficients of a matrix D with 3×19 coefficients in equation (1) were obtained from the colour patch data of the reference target using the Matlab 'charac3.m' function. For third-order polynomial regression, the 'charac3.m' and 'polyconvert3.m' functions were used [8]. The coefficient matrix showed that the majority (10 out of 19) of the higher-order terms had zero coefficients, and so did not contribute to the characterization. The camera could therefore be well characterized by a 3×9 matrix (with coefficients to four significant places) in only the second-order terms R, G, B, $R^2$, $G^2$, $B^2$, RG, GB, RB.

The calculated $XYZ$ tristimulus values were transformed into CIELAB space and the differences between these values and the reference values were calculated, as shown in Table 1.

**Table 1: Characterization of digital camera with 3rd order polynomial model**

| Target | Avg. *ΔE** | Max *ΔE** | Min *ΔE** | Median *ΔE** |
|---|---|---|---|---|
| Reference target | 4.74 | 17.84 | 0.01 | 4.34 |
| Training target | 4.90 | 17.45 | 0.20 | 3.91 |

$$\begin{bmatrix} X \\ Y \\ Z \end{bmatrix} = D \begin{bmatrix} R \\ G \\ B \\ R^2 \\ G^2 \\ B^2 \\ R^3 \\ G^3 \\ B^3 \\ RG \\ GB \\ RB \\ GR^2 \\ RG^2 \\ RB^2 \\ BR^2 \\ BG^2 \\ GB^2 \\ RGB \end{bmatrix} \tag{1}$$

Colour differences were calculated for both reference target and training targets. Mean values of $\Delta E^*_{ab} < 5$ for both the targets are considered acceptable. Histograms of colour differences with 3rd order polynomial regression for reference target and training target are shown in Figs. 8 and 9. The largest errors occurred for dark and colourful glass tiles.

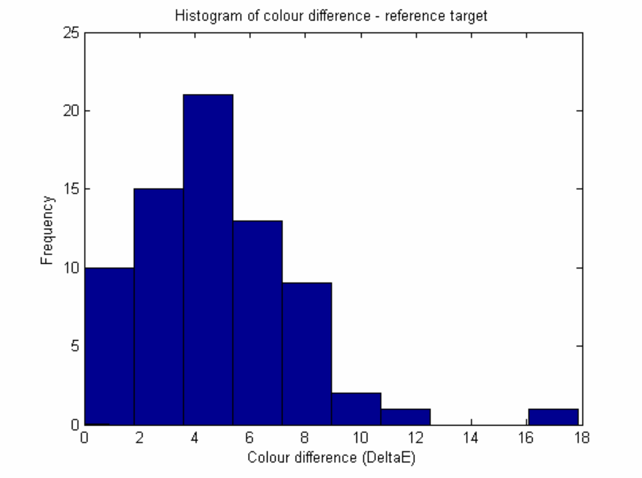

***Figure 8****. Histograms of colour difference with 3rd order polynomial regression for reference target.*

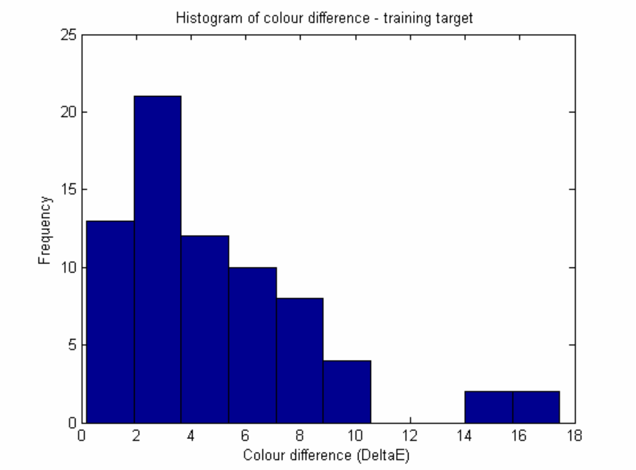

***Figure 9**. Histograms of colour difference with 3rd order polynomial regression for test target.*

## Profiling of Wide-format Inkjet Printer

The Inca 'Eagle' wide-format inkjet printer was kindly made available by Concorde Graphics (London) for printing onto transparent material. This huge flatbed printer is employed in the "grand format" reprographics printing industry, to print with UV-curing inks onto a sheet of any substrate material up to 8×4 feet in size. Both single-pass (single layer of CMYK inks) and double-pass (two layers of CMYK inks) print modes can be used. For this study, a clear acetate sheet of 20 micron thickness was selected as the substrate.

A colour test chart (IT8.7/3) was printed onto acetate sheet with 'colour management off' setting, using both single-pass and double-pass printing modes. The colour patches on each chart were measured using the GretagMacbeth SpectroscanT (transmissive) spectrophotometer, with 0/diffuse geometry. ICC profiles for each mode of printing were created with GretagMacbeth ProfileMaker software, using the IT8.7/3 reference file and the measurement files. Neutral grey perceptual rendering intent with LOGO classic gamut mapping variant and D65 light source were selected as parameters. An independent test chart TC3.5 was chosen to evaluate the colour accuracy of the printer profiles.

For evaluation of profiles, a 'round-trip test' was used to determine the combined colour accuracy of the forward and reverse transformations. For this test, an image in Lab mode was converted to CMYK (i.e. the print device colour space with absolute colorimetric rendering intent) and this CMYK image was again converted back into an Lab image. The final Lab values were compared pixel by pixel with the starting Lab values and $\Delta E^*_{ab}$ was calculated.

Fig. 10 compares the colour gamuts of the single-pass and double-pass printer profiles, together with a scatter plot of stained glass tiles (in the test chart) in the $a^*$-$b^*$ plane. As expected, the gamut of the double-pass profile is larger than that of the single-pass profile, especially in the orange to yellow range of hues, due to the extra layer of inks and consequent increase in colorant density. Some of the points representing stained glass tiles are still outside the gamut of the double-pass profile, and for these saturated tiles a colorimetric reproduction is not possible.

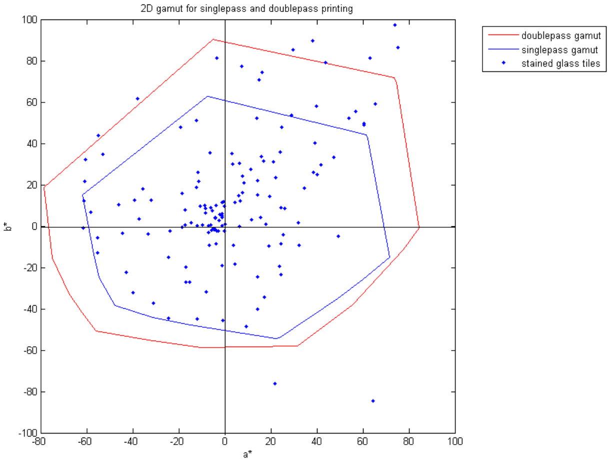

***Figure 10**. Colour gamut of single-pass and double-pass profiles and distribution of stained glass tiles in the a*-b* plane.*

Table 2 shows the average, maximum and minimum values of errors for both the profiles using IT8.7/3 and TC3.5 test charts. As the IT8.7/3 chart had been used for creating the profiles, its error values were less than those of the TC3.5 chart, but the $\Delta E^*_{ab} < 2$ for both charts was considered acceptable. Although generally in colour management systems the mean $\Delta E^*_{ab}$ values after round-tripping are expected to be less than 1, the error values in this case are sufficiently low, considering the nature of the colour measurements of the transmissive material and the variable consistency of inking of the printer.

**Table 2: Printer profile evaluation**

| Profile | IT8.7/3 | | | TC3.5 | | |
|---|---|---|---|---|---|---|
| | Mean $\Delta E^*$ | Max $\Delta E^*$ | Min $\Delta E^*$ | Mean $\Delta E^*$ | Max $\Delta E^*$ | Min $\Delta E^*$ |
| Single-pass | 1.95 | 7.90 | 0.00 | 2.07 | 7.24 | 0.00 |
| Double-pass | 1.27 | 5.00 | 0.00 | 1.20 | 6.37 | 0.00 |

Results obtained for evaluation of printer profiles are shown in Figs. 11 and 12 in terms of the histograms of colour differences ($\Delta E^*_{ab}$) for single-pass and double-pass printing. The independent test chart TC3.5 was used along with the IT8.7/3 chart to evaluate the profiles.

## Visual Evaluation

An experiment was conducted to evaluate the quality of two life-size reproductions of a stained glass panel. For this purpose, the stained glass panel (Fig. 13) was placed on the large light table and captured using the Leica Digilux II camera. The image was transformed to LAB using the polynomial characterization of the camera. The single-pass and double-pass printer profiles were applied separately to the captured digital image. These two images with embedded profiles were printed onto clear acetate substrate using the Inca 'Eagle' wide-format ink jet printer.

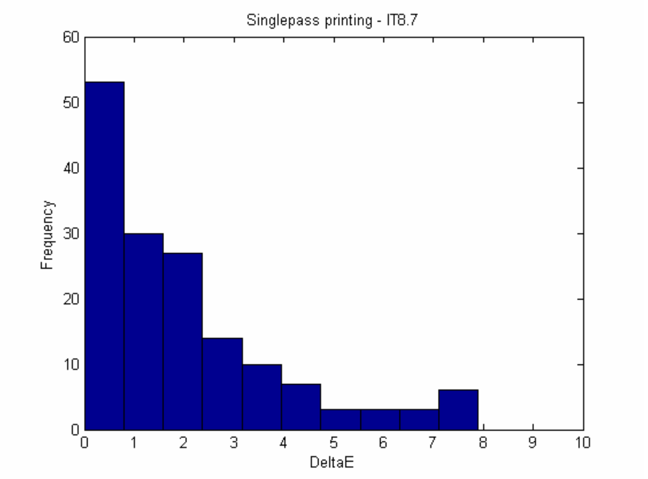

***Figure 11**. Histogram of colour differences for single-pass printing profiles using the IT8.7/3 test chart*

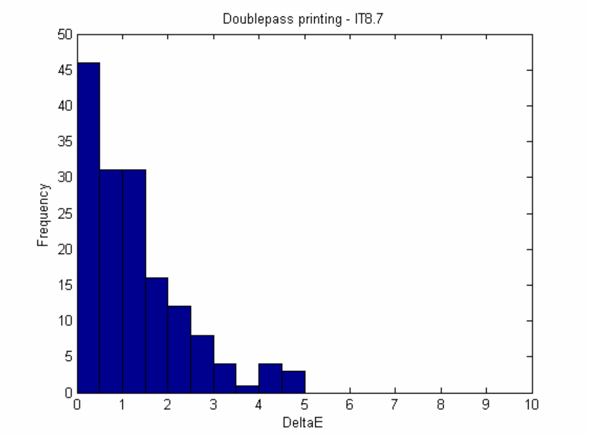

***Figure 12**. Histogram of colour differences for double-pass printing profiles using the IT8.7/3 test chart*

Each of the two printed reproductions was compared side-by-side with the original stained glass panel, backlit by the large light table. The category judgment method was used for the evaluation, the attributes judged being colour saturation, sharpness and overall quality. Twenty-two observers took part in the psychophysical experiment. Each observer was asked to compare the printed reproduction with the original stained glass panel and to assign a number according to the following categories: 1. Does not match at all; 2. Very poor match; 3. Poor match; 4. Average match; 5. Close match; 6. Very close match; 7. Exact match.

The results of the evaluation are shown in Fig. 14. The reproduction with double-pass printing was preferred by all observers to that with single-pass printing. According to this experiment, the double-pass image (average score 5.3) more closely matched the original than the single-pass image (average score 4.0). The visual results agree with the colour difference metrics ($\Delta E^*_{ab}$) as shown in Table 2, which showed that the double-pass process gave better accuracy than single-pass process.

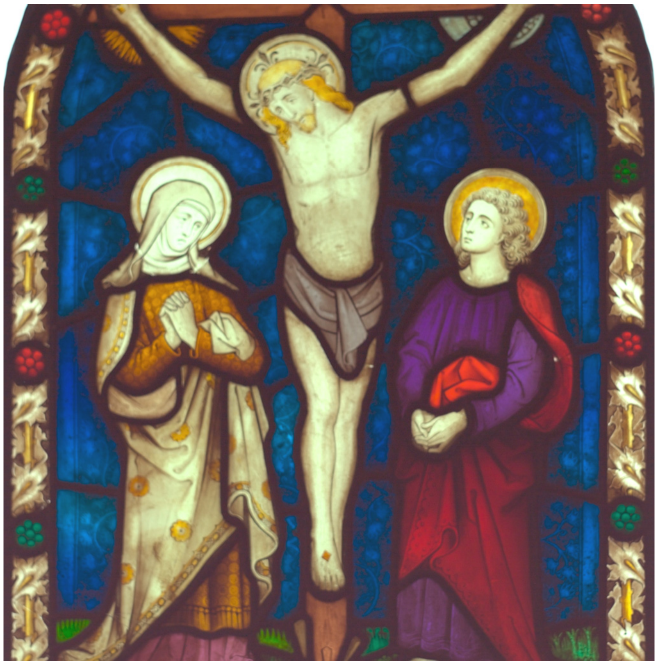

***Figure 13**. Detail of stained glass panel used for the investigation. The original panel has dimensions of approximately 59x39 cm, and is Victorian in style, fabricated in England c.1860. It was originally located in Armley Hall, Leeds, UK. Courtesy of the York Glazier's Trust.*

Although a true colorimetric reproduction of all colours in the stained glass test targets and window panel could not be achieved, this study showed that it was possible to obtain printed reproductions that were acceptably close to the original and able to serve as visual surrogates. The third-order polynomial model was sufficiently accurate for characterizing the digital camera with moderate $\Delta E^*_{ab}$ error values. The double-pass printing process showed better performance than the single-pass process for overall image quality and both were successfully characterized by means of ICC profiles. It can be concluded that colour management methods may be successfully implemented for transmissive materials, provided that the colour measurements for these materials are accurate and that controlled illumination and viewing conditions are maintained.

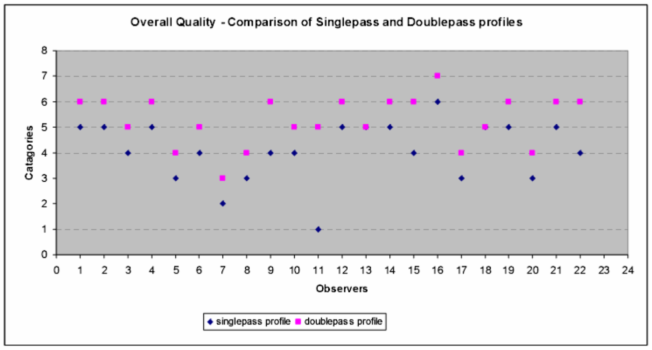

***Figure 14**. Results of category judgment experiment for overall image quality.*

## References

[1] K. Nassau, "The Physics and Chemistry of Color", 2nd Ed., John Wiley. (2001)

[2] S. Brown, "Stained Glass: An Illustrated History", Bracken Books: London (1995).

[3] L. MacDonald and J. Oldfield, "Image capture and restoration of medieval stained glass", Proc. 4th IS&T/SID Color Imaging Conference, Scottsdale, Arizona, pp. 44-49 (1995)

[4] K. Findlater, (2000) Direct Digital Image Capture of Stained Glass, The Royal Photographic Society Imaging Science Group Annual Conference, Harrow (2000).

[5] R. Song, "Characterization of Digital Camera", Veridical Imaging of Transmissive and Reflective Artifacts (VITRA), Deliverable Project Report D12, Annex 1 (2004)

[6] G. Hong, M.R. Luo and P. Rhodes, "A study of digital camera colorimetric characterization based on polynomial modeling", Color Res. Appl., 26(1) (2001)

[7] L. MacDonald, T. Song, G. Hong and K. Findlater, "Characterizing a Digital Camera for Stained Glass", Proc. AIC Symposium, Granada (2005).

[8] P.J. Green, "A Colour Engineering Toolbox", http://www.digitalcolour.org/toolbox.htm (2003)

## Author Biographies

*Kiran Deshpande received his B.E. in printing and graphics communication from the University of Pune, India (2002) and his MSc in Digital Colour Imaging from London College of Communication (2006). His research interests include colour appearance and colour management solutions.*

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